

Long List of Potential Drilling Techniques for Drilling 200-m Deep Bore on Mars in Support of Subsurface Sampling

System			Description of Sub-systems								
No.	Name of Drilling Method	Refs.	Rock and Soil Comminution	Drill Conveyance	Drill Cuttings Transport	Well Stabilization	Power Transmission	Bottomhole Power Conversion	PM&C ¹¹ Downhole Telemetry	Downhole Thermal Management	
Surface Percussion Drills Rotary percussion drills with surface power units that reciprocate and rotate the drill stem to power a down hole bit or core head.											
A	Jack Hammer Drifter	[1, 18]	Mech. Rotary/ Percussion	T&C ⁴ Drill Steel ¹	Pneumatic	Densified Wall	Pneumatic	Mechanical Reciprocation/Rotary/Pneumatic	Percussion Impact Rotary Indexing	DHT ¹² not supported	Air Cooling
B	Sonic Drill Mechanical Vibrator	[7, 19]	Mechanical Percussion/ Rotation	T&C Drill Rods	Continuous Core	Densified Wall	Mechanical Reciprocation / Rotation	Mechanical Reciprocation / Rotation	Percussion Impact Rotary Indexing Kerf Core Head	DHT not supported	Bit to Drill Rod to Rock and Core
C	Ultrasonic/sonic drill/corer	[17]	Mechanical Percussion	T&C Drill Rods	Continuous Core	Densified Wall	Mechanical Reciprocation	Mechanical Reciprocation	Percussion Impact Kerfing Corehead	DHT not supported	Bit to Drill Rod to Rock and Core
Cable Deployed Drills Drilling assemblies deployed on a mechanical wireline (sandline) or electric wireline (mechanical, telemetry, and/or electric power)											
A	Percussion Churn Mud ¹	[1,18]	Mechanical Percussion	Umbilical Sandline ⁵	Mud Slurry Bailer	Filter Cake / Densified Wall	Mechanical Reciprocation	Mechanical Reciprocation	Gravity Accelerated Impact w/Cable Wrap Indexing	DHT using Wireline	Bit to Liquid to Formation
B	Percussion Churn Air ²	[1,18]	Mechanical Percussion	Umbilical Sandline ⁵	Scow Bailer / Bucket Auger	Densified Wall	Mechanical Reciprocation	Mechanical Reciprocation	Gravity Accelerated Impact w/Cable Wrap Indexing	DHT using Wireline	Bit to Cuttings to Formation
C	Electrodrill	[7]	Mechanical Rotary	Umbilical Wireline w/power cable ¹	Mud Slurry Bailer	Filter Cake / Densified Wall	Electric	Electric	Rotary Gouge / Electric Motor	DHT using Wireline	Bit to Liquid to Formation
Rotary Drills Drilling assemblies deployed on segmented drill stem and rotated from the surface with a rotary table on the rig floor or a top drive power swivel.											
A	Mud Rotary	[1, 2, 3]	Mechanical Rotary	T&C Drill Pipe ⁴	Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Hydraulic Rotary / Hydraulic	Hydraulic Rotary / Hydraulic	Rotary Gouge (Percussion Impact multi-cone)	Mud Pulse Telemetry	Liquid Cooling
B	Air Rotary	[4, 18]	Mechanical Rotary	T&C Drill Pipe	Pneumatic Slurry	None, TBD ⁶	Mechanical Rotary / Pneumatic	Mechanical Rotary / Pneumatic	Rotary Gouge (Percussion Impact multi-cone)	Drill Stem Acoustic Telemetry	Air Cooling
C	Mud Diamond (Kerf) Coring	[5, 18]	Mechanical Rotary	T&C Drill Rods ⁴	Continuous Core ⁹ /Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Mechanical Rotary / Hydraulic	Mechanical Rotary / Hydraulic	Rotary Gouge Core Head	DHT not supported	Liquid Cooling
D	Air Diamond (Kerf) Coring	[4, 5, 18]	Mechanical Rotary	T&C Drill Rods	Continuous Core ⁹ /Pneumatic Slurry	None, TBD	Mechanical Rotary / Pneumatic	Mechanical Rotary / Pneumatic	Rotary Gouge Core Head	DHT not supported	Air Cooling
Downhole Motor and Rotary Hammer Drills Dndexing motor) but telemetry is more difficult.											
A	Mud Powered Hydraulic Motor ²	[3, 6]	Mechanical Rotary/ Percussion	Continuous Tubing ¹	Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Hydraulic	Hydraulic	Rotary Gouge Percussion Impact / Hydraulic Motor/Hammer	Telemetry Cable in Continuous Tubing	Liquid Cooling
B	Air Powered Pneumatic Motor	[4]	Mechanical Rotary/ Percussion	Continuous Tubing	Pneumatic Slurry	Densified Wall	Pneumatic	Pneumatic	Rotary Gouge Percussion Impact / Pneumatic Hammer/Motor	Telemetry Cable in Continuous Tubing	Air Cooling
C	Electric Motor with Air Cooling	[7, 8, 9, 10]	Mechanical Rotary	Umbilical Wireline ⁵ w/power cable	Pneumatic Slurry	None, TBD	Electric / Pneumatic	Electric / Pneumatic	Rotary Gouge (Percussion Impact multi-cone) / Electric Motor	DHT using Wireline	Air Cooling
D	Ultrasonic Drill	[11, 17]	Abrasion and Cavitation	Continuous Tubing w/Utilities ¹	Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Electric / Hydraulic	Electric / Hydraulic	Electric or Hydraulic Acoustic Horn	Telemetry Cable in Continuous Tubing	Liquid Cooling
Piercing Soil Drills Soil piercing and ramming assemblies deployed on segmented push rods design to transmit high compressive impact loads.											
A	Thrust boring	[20]	Local formation compaction	T&C Push Rods ⁴	Displaced into adjoining soil	Densified Wall	Mechanical Axial Translation	Mechanical Axial Translation	Direct Mechanical Compaction	DHT not supported	Pierce Mandrel to Push Rod to Soil
B	Impact Drilling	[20]	Local formation compaction	T&C Push Rods	Displaced into adjoining soil	Densified Wall	Mechanical Axial Translation	Mechanical Axial Translation	Direct Mechanical Compaction	DHT not supported	Pierce Mandrel to Push Rod to Soil
Overburden Drilling Systems Drilling systems based on advancing a casing for borehole stabilization in unstable surface formations while or before drilling a smaller diameter hole to penetrate harder formation where these systems will not drill.											
A	Impact Ram Piercing	[20]	Coring, Local Compaction, Erosion	Special Piercing Casing	Plug Core / Compacted in adjoining soil	Casing While Drilling, Densified Wall	Mechanical Axial Translation / Hydraulic	Mechanical Axial Translation / Hydraulic	Direct Mechanical Compaction	DHT not supported	Liquid Cooling/Pierce Mandrel to Push Rod to Soil
B	Hollow stem auger	[18]	Mechanical Rotary	Hollow stem auger sections	Auger + Continuous Core	Casing While Drilling	Mechanical Rotary	Mechanical Rotary	Auger Screw	DHT not supported	Auger Drill Stem to Formation
C	Eccentric Reamer ODEX ⁸	[18]	Mech. Rotary/ Percussion	Drill Pipe + Special ODEX TM Casing ⁸	Pneumatic Slurry	Casing While Drilling	Mechanical Reciprocation/Rotary/Pneumatic	Mechanical Reciprocation/Rotary/Pneumatic	Rotary Gouge Percussion Impact	DHT using WLDHC ¹³	Air Cooling
D	Dual Rotary Drilling	[18]	Mechanical Rotary	Drill Pipe + Special LH Thrd. ⁸ Casing	Pneumatic Slurry	Casing While Drilling	Mechanical Rotary/Pneumatic	Mechanical Rotary/Pneumatic	RH Rotary Gouge Bit / LH Rotary Gouge Casing Shoe	DHT using WLDHC	Air Cooling
E	Wireline Retractable Drill/Casing Advancer	[18]	Mechanical Rotary	Casing Shoe w/Wireline Bit Replacement	Pneumatic Slurry	Casing While Drilling	Mechanical Reciprocation/Rotary/Electric/Pneumatic	Mechanical Reciprocation/Rotary/Electric/Pneumatic	Rotary Gouge Percussion Impact	DHT using Wireline	Air Cooling
Subterranean Moles Suid circulation and cuttings disposal.											
A	Guided Impact Mole	[20]	Local formation compaction	Self propelled mole / umbilical	Displaced into adjoining soil	Densified Wall	Hydraulic or Pneumatic	Hydraulic or Pneumatic	Direct Mechanical Compaction	DHT using cable in Umbilical	Pierce Mandrel to Soil and Power Fluid
B	Percussion Mole	[JPL+RDS]	Mech. Rotary/ Percussion	Self propelled mole / umbilical	Repack cuttings behind the mole	Densified Wall and Re-packed Hole	Hydraulic or Electric	Hydraulic or Electric	Percussion Impact Rotary Indexing / Electric Motor	DHT using cable in Umbilical	Mole to Cuttings and Rock (and Umbilical?)
Jet and Cavitation Drills Dquired.											
A	High Pressure Continuous or Pulsed	[12]	Hydraulic Impact/Erosion	Continuous Tubing w/Utilities	Hydraulic Slurry	Filter Cake or Densified Wall	Hydraulic	Hydraulic	Continuous or Pulsed Hydraulic Jet	Telemetry Cable in Continuous Tubing	Liquid Cooling
B	Cavitating Jets	[7, 12]	Hydraulic Impact/Cavitation	Continuous Tubing w/Utilities	Hydraulic Slurry	Filter Cake or Densified Wall	Hydraulic	Hydraulic	Implosion of Vapor Cavities in a Jet	Telemetry Cable in Continuous Tubing	Liquid Cooling
C	Electric Spark Drill	[12]	Hydraulic Impact/Cavitation	Continuous Tubing w/Utilities	Hydraulic Slurry	Filter Cake or Densified Wall	Hydraulic	Hydraulic	Electric Spark Shock Wave Generator	Telemetry Cable in Continuous Tubing	Liquid Cooling
D	Abrasive Jets	[7, 12]	Particle Impact/Erosion	Continuous Tubing w/Utilities	Pneumatic Slurry	None, TBD	Pneumatic	Pneumatic	Acceleration of Particles in a Pneumatic Expansion Jet	Telemetry Cable in Continuous Tubing	Air Cooling
E	Supercritical CO2 Jet Rotary Drill	[13]	Chemical/Hydraulic Erosion/Mech.	Continuous Tubing w/Utilities	Pneumatic Slurry	None, TBD	Pneumatic / Chemical / Mech. Rotary	Pneumatic / Chemical / Mech. Rotary	Rotary Gouge/ High Velocity Jets / Pneumatic Motor	Telemetry Cable in Continuous Tubing	CO2 Circulation
Thermal Spallation Drills Dation of the jet(s) is required.											
A	Flame Jet Spallation	[12, 14]	Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Partial glass lining	Chemical / Pneumatic	Chemical / Pneumatic	Chemical Combustion / Thermal Spallation	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
B	Rocket Exhaust	[11, 12]	Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Partial glass lining	Chemical / Pneumatic	Chemical / Pneumatic	Chemical Combustion / Thermal Spallation	Telemetry Cable in Continuous Tubing	Water circulation and steam formation
C	Microwave Spallation	[7, 11]	Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Partial glass lining	Electric / Pneumatic	Electric / Pneumatic	Microwave Generator / Thermal Spallation	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
D	Thermal Shock (Reverse Spallation)	[7, 21]	Reverse Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Freezing moisture in formations	Cryogenic gas/liquid flow	Cryogenic gas/liquid flow	Cryogenic Expansion / Thermal Spallation	Telemetry Cable in Continuous Tubing	Cryogenic Fluid Expansion
Rock Melting Drills These are a family of systems based on partial or complete fusion of rock to produce a densified cast bore lining and excess melt removed by extrusion & solidification of small particles.											
A	Rock Melting Drill	[7, 11, 12, 15]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Electric / Pneumatic	Electric Heater / Fusion	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
B	Microwave Melting	[7]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Electric / Pneumatic	Microwave Generator / Fusion	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
C	Electric Arc and Plasma	[7, 11, 12]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Electric / Pneumatic	Spark or Arc Plasma Heater / Fusion	Telemetry Cable in Continuous Tubing	Water Circulation
D	Laser Drill	[7, 11, 12]	Thermal Fusion /Spallation	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Melted and fused bore wall	Electric / Pneumatic	Electric / Pneumatic	Optical Absorption Heating / Fusion / Stress Wave Generation	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion

Footnotes	
1	Mud implies liquid drilling fluids including water, natural mud, bentonite base mud, or polymer-based mud.
2	Air implies Martian atmosphere primarily CO ₂ at a uncompressed pressure of 800 Pa + ~200 Pa.
3	Motor and/or Hammer implies downhole transmitted power conversion to rotary and/or reciprocating mechanical
4	T&C = threaded and coupled segmented drill stem. Drill steels are hollow, thick-walled steel rods designed to convey high reciprocating compressive loads from the surface to the bit. Drill pipe has externally/internally upset tool-joint-connection design for high tensile and torsion loads and a pipe diameter of 0.2 to 0.7 times the bore diameter. Drill rods have flush-joint external connections and a pipe diameter > 0.7 times the bore diameter that is designed for high speed rotation obtaining laterally significant support from contact with the bore wall. Push rods are 3 to 5-ft (1 to 1.7-m) long, threaded and coupled solid rods or heavy wall steel tubes. Continuous Tubing is coiled or reeled tubing that is inserted and retracted from the bore much like a wireline and can be inserted and retracted with out cessation of circulation, power transmission, or telemetry. Umbilical are flexible wirelines or tethers with telemetry and power cable, and hydraulic/pneumatic hoses.
5	A sandline is a structural steel wire cable with no copper or fiber optic telemetry. A wireline is a telemetry (wire or fiber optic) cable wrapped inside a structural steel armor cable so that the entire cable is self-supporting in a deep hole.
6	TBD = to be determined. Commercial system or prototype technology is unknown or does not exist or effect of drilling method on hole stability is not obvious or known.
7	w/Utilities = with utilities installed inside of the tube or cable that may include telemetry or fiber optic cables, and electric power cable, and/or hydraulic or pneumatic tubing.
8	ODEX TM = overburden eccentric drilling. Commercial advanced casing-while-drilling system for shallow unconsolidated and unstable formations [1]. The system uses an under-reaming bit that can be run and withdrawn through the casing. The bottom of the casing is tipped with hard facing and the casing is advanced with percussion.
9	LH Thread. = Left hand threaded casing. Casing is advanced with a dual rotary table that Right Hand rotates a conventional drilling system with an eccentric, extractable, under-reaming bit inside a Left Hand rotating casing string with a rotary drilling shoe on bottom.
10	Continuous Core with thin wall T&C drill stem, drill rods or hollow stem augers supports wireline core retrieval.
11	PM&C = process monitoring and control – Long list addresses downhole telemetry presently supported or conceptually supported in the system concept proposed
12	DHT = downhole telemetry support through or in drill stem. Telemetry for some systems is not supported in commercial or prototype systems that we are aware of.
13	WLDHC = wireline downhole connection. This is a wireline that is run through a top drive rotary swivel or surface tubing thruster and through the inside of a T&C drill stem or push rod after the bit is set on the bottom of the hole. It is then plugged into the bottom-hole assembly using wet-connect technology that would be a dry connection in air drilling or thrust boring.

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